"ZFX--A 350 kJ, 2MA, Z-Pinch Driver"

J.D. Sethian and A.E. Robson
Naval Research Laboratory
Plasma Physics Division
Washington, D.C. 20375

INTRODUCTION

ZFX is a new pulse generator designed to drive up to 2 MA into a dense z-pinch formed from a frozen deuterium or D-T fiber. In previous experiments carried out at NRL[1], this type of pinch was observed to be stable as long as the current was rising. In those experiments, the current was limited by the 640 kA capability of the POSEIDON[2] generator, and the pinch temperature was too low to produce a significant number of thermonuclear reactions. ZFX has been designed to increase the current by a factor of three while maintaining the same 4 kA/nsec rate of rise as POSEIDON. (This relatively slow rate of rise is believed to be a key to the pinch stability.) Simple models[3] predict that, provided the stability is maintained for the longer time, a 2 MA pinch formed from frozen D-T should achieve thermonuclear breakeven.

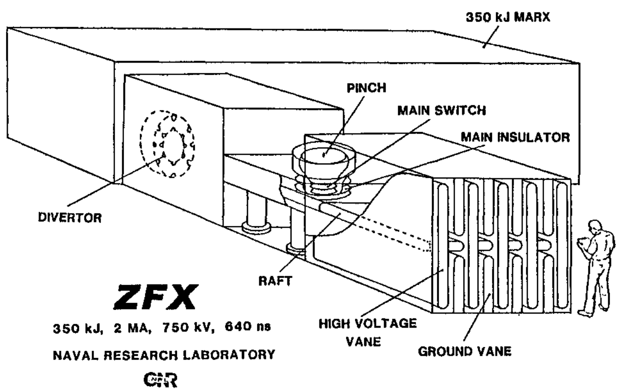

Figure 1: ZFX perspective view

ZFX consists of a 350 kJ Marx that charges two 0.575 μF, 750 kV capacitors which are connected in parallel and situated on either side of the output switch and pinch chamber (Fig 1 and 2).

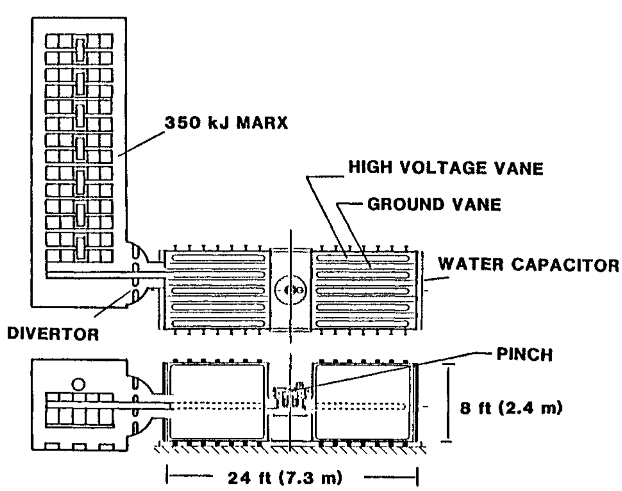

Figure 2: ZFX plan view

At maximum charge, peak voltage across the pinch will be 500 kV. The current waveform for the 100 nH pinch load is sinusoidal, with a quarter period (risetime) of 640 nsec and a maximum value of 2.0 MA. The predicted waveforms for ZFX driving a fixed 100 nH load are shown in Figure 3.

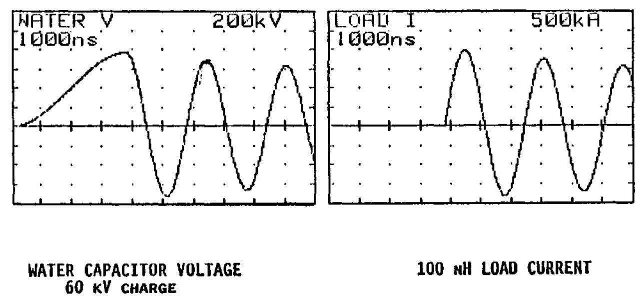

Figure 3: Predictions for ZFX at full charge

THE MARX

The Marx is assembled from components obtained from two ANTARES Marx generators. These were originally built by Maxwell for Los Alamos National Laboratory.[4] The oil insulated Marx is connected in a plus/minus configuration, and consists of fourteen half stages with each half stage comprised of five 2.8 μf, 60 kV capacitors. Thus there are a total of seven switches. The first four are triggered with an independent 280 kV trigger Marx, the remaining three by passive networks. The erected capacitance and voltage of the main Marx are 1.0 μf and 840 kV, respectively, and the charging time of the water capacitor is 4 μsec. A photo taken inside the Marx is shown in Figure 4.

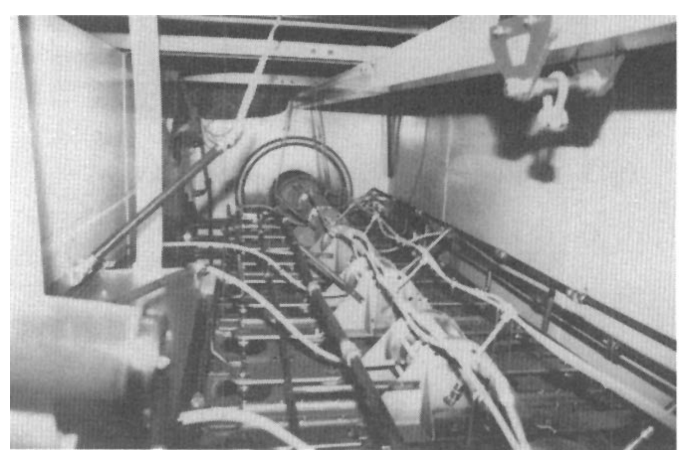

Figure 4: Photo of ZFX Marx

One of the interesting features of the Marx is its method of support: As space limitations prevented hanging the Marx with nylon straps as in the conventional manner, it was necessary to support the

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 1989	**N/A**	**-**

4. TITLE AND SUBTITLE	
"ZFX--A 350 kJ, 2MA, Z-Pinch Driver"	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Research Laboratory Plasma Physics Division Washington, D.C. 20375**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Marx from below. The support is segmented so each full stage (ten capacitors) has its own platform. Each platform consists of a 60" long by 29" high by 1" thick lucite plate supported by six 5 gallon plastic buckets filled with wax and sand. The buckets are arranged on one of three steel channels that are welded to the Marx tank floor. Six 4" diameter by 3" long lucite pegs are glued into the plate and cast into epoxy that fills the upper 3" of each bucket. The epoxy makes each platform a monolithic structure and also prevents the transformer oil from dissolving the wax. This technique has proven to be very inexpensive, extremely strong both mechanically and electrically, and readily accessible for maintenance. The Marx has been tested successfully at full voltage into a resistive load.

THE WATER CAPACITOR

The water capacitor is of a novel design for a high voltage pulsed power device, but rather mundane for an electronic circuit component; it is basically a number of parallel plate capacitors connected in parallel. The plates are enclosed inside two boxes, each 96" tall by 96" wide by 120" long, that are connected to each other by a 48" wide enclosed bridge. Running inside the boxes, from the outer end of one box, inside the bridge, and to the opposite end of the other box, is a 90" wide by 281" long by 7" thick "raft". The raft, which is made from aluminum sheets riveted to an aluminum frame, is supported in the bridge section by four lexan supports. In each box section the horizontal raft has suspended from it five vertical high voltage vanes, which are fabricated by riveting .050" thick aluminum sheets to a frame made from aluminum tubes. The high voltage vanes are 104" wide by 80" high by 7" thick. In between them are the ground vanes, constructed in the same manner, but connected directly to the floor or ceiling of the boxes. The spacing between the vanes is 3" in the parallel regions and 4" between the rounded edges and the nearest flat surfaces. These dimensions were chosen (using a potential plot program[5]) so that the field between all the conductors would be a uniform 100 kV/cm at full charge. In order to ensure that the fields are uniform, the spacing between the vanes was held to a tolerance of 1/8". A photo of the water capacitor before assembly of the outside boxes is shown in Figure 5.

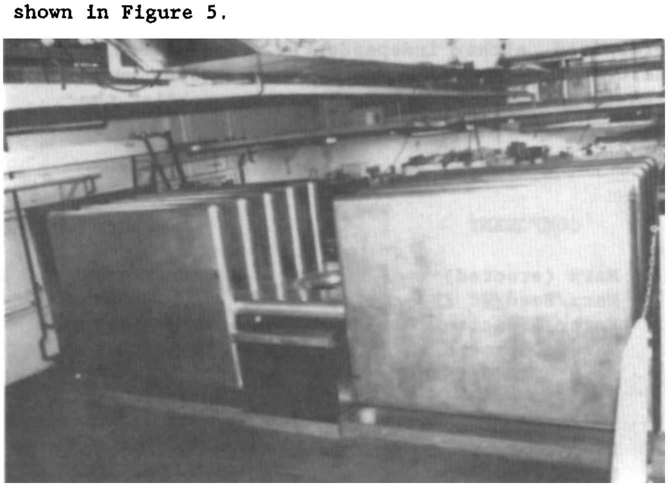

Figure 5: Water Capacitor under construction

The boxes themselves are constructed from aluminum sheets that are riveted, sealed with Bostik 920 adhesive, and filled with 7 MΩ-cm water. To withstand the hydrostatic pressure of the eight foot head of water, 1" thick plywood panels are bonded to the aluminum sheet. The plywood in turn is supported with structural steel beams. The completed ZFX is shown in Figure 6.

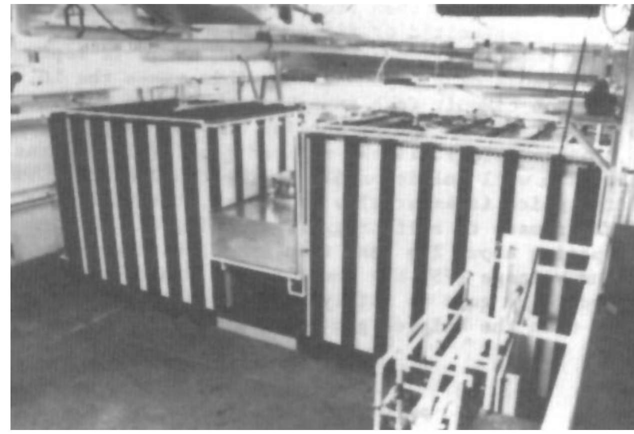

Figure 6: The completed ZFX Facility

Note that this parallel plate arrangement has a relatively high mean energy density, owing to the fact that about 31.3% of the volume of water is used to store the energy. In fact, as shown graphically in Figure 7, the total volume of ZFX is about one third of what would be required if it were built as a pulseline, because the latter uses only about 9.1% of the water for energy storage. In addition to requiring substantially less real estate (which means it can fit in the lab) a water capacitor is also more efficient electrically; for a given amount of stored energy it can drive about 10% more current through an inductive load than a pulseline.

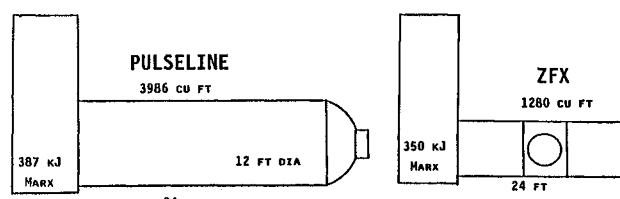

Figure 7: Comparison between ZFX and a pulseline capable of the same performance.

LOAD CHAMBER / OUTPUT SWITCH

The front end of ZFX is shown in Figure 8. The main switch is located on top of the raft in the bridge section, and the load chamber is located directly above it. The current flow is along the high voltage vanes towards the center of the raft, through the switch and load, and back through the ground vanes.

The switch itself is a self-triggered version of the "RIMFIRE" switch developed at Sandia[6], which we have dubbed the "STRIMFIRE" switch, for Self Triggered RIMFIRE Switch. It consists of four isolated 29 cm o.d., 23 cm i.d. electrode rings which are mounted on a lexan disc and separated from each other with polyethylene spacers. Thus there are a total of five electrode gaps, with the spacing between them approximately 1.5 cm. The spacers and electrodes are skewered on a 10 cm diameter polyethylene bolt which not only centers the switch components, but also provides the tension to keep the switch housing together as it is pressurized. The switch housing itself is composed of lexan and aluminum in a conventional z-stack insulator configuration, the only difference being that the components are glued together to prevent them from shifting when the switch is either pressurized or fired. As in the Sandia concept, the capacitance between each stage is kept small; in this case around 29 pF. This makes the LC time of the circuit fast enough so that when the first gap fires, its voltage is applied only across the next gap, rather across all the unfired gaps. This ensures the switch will multichannel. Unlike the Rimfire switch, which is externally triggered, the Strimfire switch is made to self trigger by making the lowermost gap spacing about 20% less than the other four. At maximum voltage (750 kV) the electric field between the secondary gaps is fairly uniform at around 95 kV/cm, with the trigger gap being around 116 kV/cm.

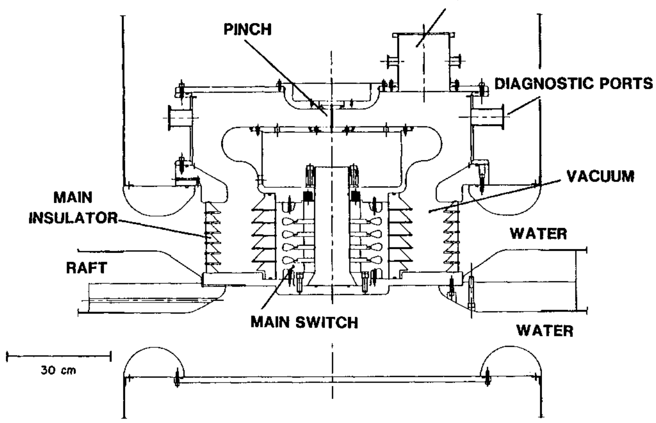

Figure 8: ZFX Front End

The front end follows currently accepted practice in that the main water/vacuum insulator is a conventional lucite/aluminum/o-ring z-stack. However, because of the unusually long pulse times and the rather luminous properties of the dense z-pinch, great care had to be taken to ensure that both the switch and main insulators were totally shielded from any ultraviolet light. All current joints were shielded, either with metal baffles or, where practical, with an o-ring inserted into a groove cut into the joint. The high voltage electrode is also extended and shaped so light from the pinch must undergo several non-specular reflections in order to illuminate the insulators.

THE DIVERTOR SWITCH

Because the area of the conductors in ZFX is rather large, on the order of 2 x 10^6 cm^2, the breakdown time for the water[7] is uncomfortably short; at full voltage it is only about twice the charging time. Consequently, if the main switch fails to fire the water capacitor could easily be overstressed. Moreover, even if the main switch does fire, the very inductive nature of the dense z-pinch means that most of the energy is deposited into the magnetic field, which is then reflected back into the water capacitor. If the water has the very high resistivity necessary for good energy transfer, this energy can slosh between the water capacitor and pinch for many cycles, and again eventually overstress the water capacitor. In either case, the resulting breakdown could conceivably damage the sheet metal on one of the vanes, and owing to the way the boxes are sealed, would necessitate a rather cumbersome repair. Thus it is highly desirable that the water capacitor be discharged through a resistive load independent of whether the main switch fires or not.

The complete divertor/Marx trigger circuit is shown in Figure 9. Two identical series LC networks are connected in parallel with the main water capacitor and its feed. These additional networks have the same LC time constant as the Marx/main feed/water capacitor circuit. (The values of all these components are given in Table I, below.) Because of the resonance between the LC networks, the voltage on the capacitor of the second auxiliary LC network rises steadily during the charging cycle, independent of the output switch behavior (see the waveforms in the lower portion of Figure 9).

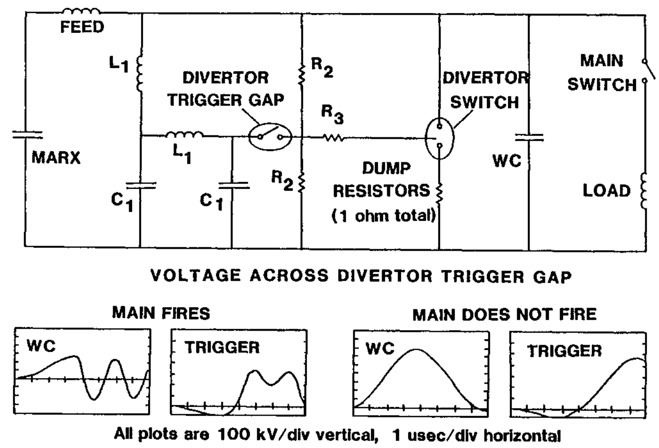

Figure 9: Divertor Circuit

This voltage breaks down a trigger gap which then triggers a divertor switch located at the output of the main Marx. The divertor consists of eight separate SF_6 insulated midplane-triggered switches, each of which connects the main feed (and consequently the water capacitor) through an eight ohm resistor to ground. Each trigger is connected to the divertor trigger circuit through a 10 kΩ resistor to maintain the voltage until all eight switches have fired.

ELECTRICAL CIRCUIT

The values of all the components of ZFX have been determined, either independently on the bench or by measuring resonances in situ. These values were then used in a transmission line code[8] to predict the behavior of the whole system (see Figure 3).

TABLE I: ZFX CIRCUIT COMPONENTS

COMPONENT	VALUE
Marx (erected)	1.15 μF
Marx/Feed/WC Inductance*	3.05 μH
Water Capacitor C	1.15 μF
Water Capacitor L	19 nH
Switch Inductance	35 nH#
Top Electrode Inductance	25 nH
Load Inductance (1" bolt)	34 nH
Load Inductance (Pinch)	100 nH
Div. Trig. Inductor (L_1)	505 μH
Div. Trig. Cap (C_1)	3.33 nF
R_2 - see Fig 9	750 Ω
R_3 - see Fig 9 (8 total)	10 kΩ

* Most of the inductance is in the Marx
# Design value

THE WATER SYSTEM

Two separate water systems are incorporated in ZFX; one to filter, purify, and deionize the water; the other to remove the dissolved air.

The requirements on water purity are somewhat more stringent than on most systems because of the relatively long charging times. Typically the water resistivity must be greater than 7 MΩ-cm in order to prevent appreciable energy loss during the charging cycle. (In other words the decay time of the water should be at least 50 μsec, in order to be long compared to the charging time of 4 μsec.) This high resistivity is attained by using a standard commercially available water purification system. Water is drawn from in between the ground vanes at the outside bottom of both boxes, sent through the purification system, and then returned through injectors on the inside walls of each box. The injectors are located between the ground vanes just beneath the raft and just below the roof. This somewhat elaborate plumbing ensures that water is adequately circulated between all the vanes. In addition to the main filtration pump, a second pump sends water from the bottom of one box to the top of the other. The resulting pressure differential keeps water flowing through the bridge section, and ensures the water around the front end is kept pure. The resistivity of the water is monitored with a conductivity meter located in one of the injector lines. Typically the water resistivity can be raised to 7 MΩ-cm in about 48 hours of circulating. However, we do not normally run with this high a value as the maximum energy transfer is not always required and high resistivity water can corrode the aluminum.

In order to maintain the designed voltage standoff, it is essential that no air pockets be trapped on the large horizontal surfaces underneath the roof and the raft. Even air bubbles as small as 1.5 mm diameter have been shown to adversely affect electrical breakdown.[9] We eliminate the air by circulating the water through a sealed, evacuated stack that extends 36 feet above the top of the water capacitor. The bottom of the stack is connected to one of the boxes, and because the top of the water capacitors are vented to atmosphere, water rises in the tube until the weight of the water is just balanced by the vacuum, which turns out to be about 30 feet above the water capacitor. The water is deaerated as it free falls six feet in the vacuum, absorbs any trapped air as it returns through the water capacitor, and is deaerated again as it is returned to the stack. This system has proven to be very effective; it can completely eliminate all the trapped air in about a week.

ZFX PERFORMANCE

To date ZFX has been run at one half full charge (30 kV on the Marx) and with the water resistivity at about 2 MΩ-cm. This corresponds to an applied voltage of about 280 kV on the water capacitor. Oscillograms for a typical shot with the load replaced with a 5 cm long, 2.54 cm diameter bolt (inductance of 34 nH) are shown in Figure 10. In the oscillogram on the left, ZFX is fired in a normal manner. i.e. all switches set properly. The arrow marks the point at which the divertor fires, as indicated by a voltage monitor connected to the divertor trigger pin (not shown). In the oscillogram on the right, the divertor trigger switch pressure was deliberately set to a very high value so the divertor would not fire. By comparing the two, it is obvious that the divertor takes all the voltage off the water capacitor in a little more than three cycles, whereas when the divertor does not fire, the voltage stays up longer. (In fact, the only reason the water capacitor voltage can be seen to decay on this timescale is because the water resistivity was purposely set to a low value of 0.7 MΩ-cm, corresponding to an RC decay time of 5 μsec, for testing purposes.)

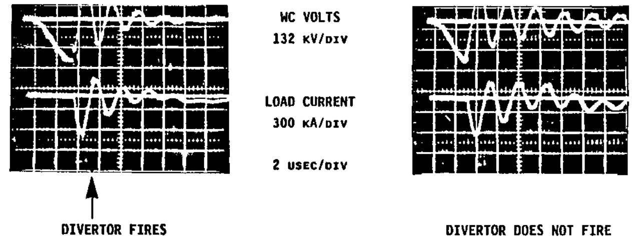

Figure 10: ZFX data with a 34nH load.

In preliminary experiments, we have driven over 700 kA into pinches formed from deuterated polyethylene (CD_2) fibers. Results from frozen deuterium fibers should be forthcoming, allowing us to fully assess the viability of the dense z-pinch as a possible alternative fusion power source.

ACKNOWLEDGEMENTS

The authors are grateful for the advice, expertise, and assistance of Mr. K.A. Gerber and Dr. A.W. DeSilva, and for the mechanical engineering support of Mr. M.O. Sy and Mr. J. Chow, the electrical engineering assistance of Mr. J.K. Burton, and the technical support of Mr. D.R. Evenson and Mr. J.P. Picciotta. The authors also thank Dr. E.A. Rose of Los Alamos National Laboratory for assisting with the transfer of the Antares components. This work was supported by The Office of Naval Research, The U.S. Department of Energy and SDIO.

REFERENCES

1. J.D. Sethian, A.E. Robson, K.A. Gerber and A.W. DeSilva, Phys. Rev Lett 59, 892 (1987). IBID 59 1790 (1987)
2. J.D. Sethian and F.M. Mora, NRL Memorandum Report #4867 Sept 1982.
3. A.E. Robson, Nuclear Fusion 28, 2171 (1988).
4. F.L. Ripe, et al. Proceedings, IEEE Pulsed Power Conference, 1979, p 254.
5. J.E. Bores, Sandia National Laboratory Report SC-RR-71-1377. 1971.
6. D.R. Humphreys, et al. Proceedings, IEEE Pulsed Power Conference, 1987, p 262.
7. J.C. Martin, private notes, Dec 1977
8. D.D. Hinshelwood, NRL Memorandum Report #5185, Naval Research Laboratory, Washington D.C. 1983.
9. V.V. Skoryh, Sov. Phys. Tech Phys. 31, 390 (1983).